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An electron beam for physics experiments based on AWAKE scheme and relevance for EuPRAXIA

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- Introduction and AWAKE
- Possible physics experiments
  - Search for dark photons, NA64-like
  - High energy electron−proton collisions, LHeC-like and VHEeP
- Summary and outlook

EuPRAXIA Workshop — Paris, 12 October 2016

Introduction

Presented first ideas on particle physics applications of AWAKE scheme at Physics Beyond Colliders Kick-Off Workshop, CERN, September 2016.

This utilises current CERN infrastructure and beams to provide the accelerator system, in AWAKE's case using bunches of protons to accelerate electrons.

There are various different techniques and some (ambitious) potential applications of plasma wakefield acceleration.

Should first consider some realistic possibilities.

Briefly present AWAKE programme and expected electron bunches to be produced.

Present some ideas of experiments that could be done and significantly benefit from this.

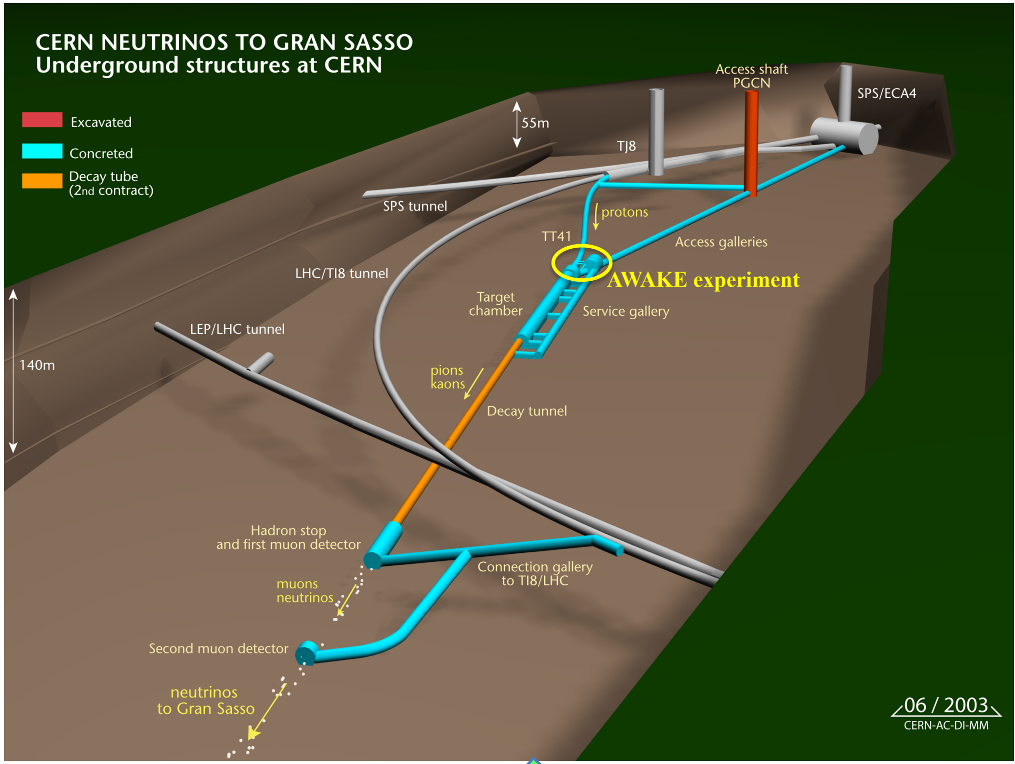
Happy to hear of other ideas of experiments that could utilise a high energy electron beam.

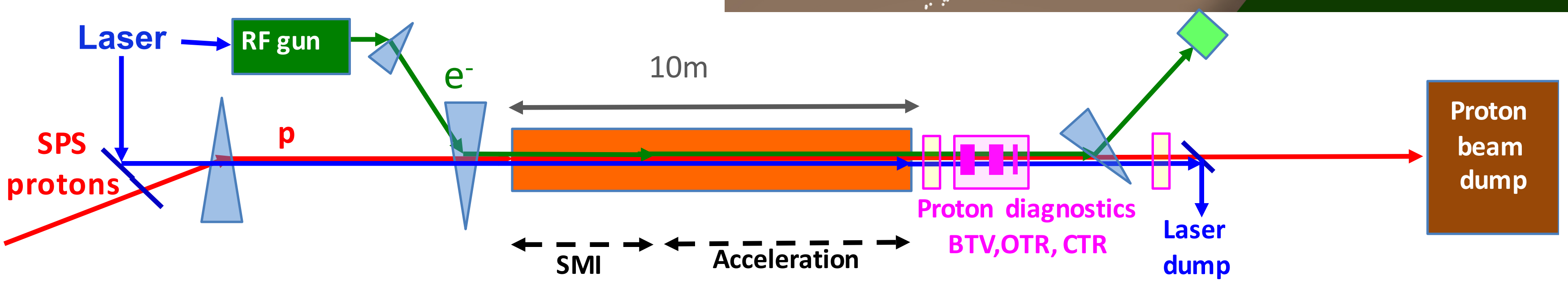
These may be applications for an electron beam from EuPRAXIA too. Present the AWAKE applications and comment on their relevance to EuPRAXIA.

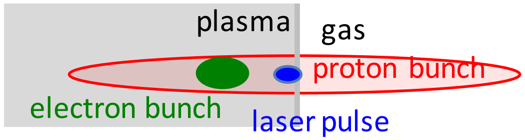
Possible new projects need to have a novel and exciting physics programme.

AWAKE: proton driven plasma wakefield experiment

- Demonstration experiment to show effect for first time and obtain *GV/m* gradients.
- Use *400 GeV* SPS proton bunches with high charge.
- To start running this year and first phase to continue to LS2.
- Apply scheme to particle physics experiments leading to shorter or higher energy accelerators.

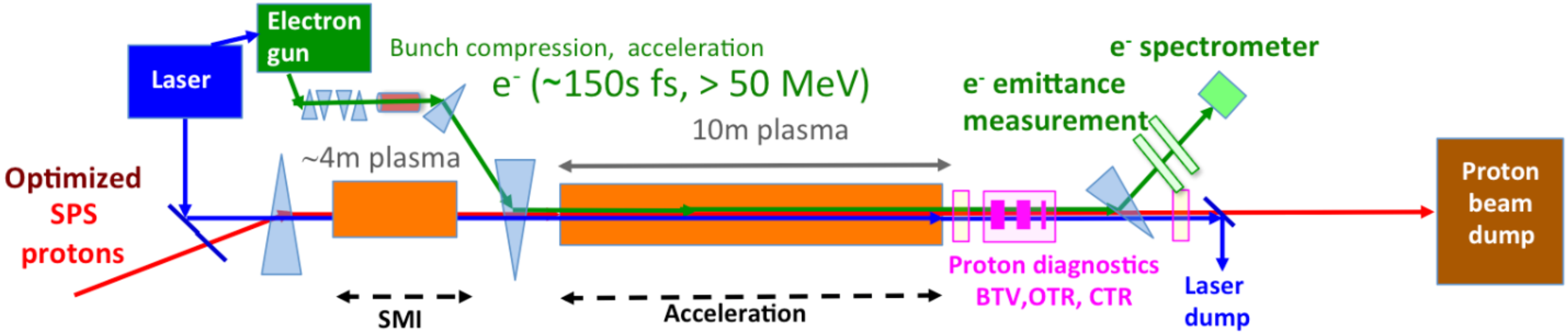






AWAKE Run 2

- Preparing AWAKE Run 2, after LS2 and before LS3.
  - Accelerate electron bunch to higher energies.
  - Demonstrate beam quality preservation.
  - Demonstrate scalability of plasma sources.



Preliminary Run 2 electron beam parameters

Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim$ 50 MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim$ 10 μm

- Are there physics experiments that require an electron beam of up to *O(50 GeV)* ?
- Use bunches from SPS with *3.5* × *10*^{11} *protons* every ~ *5 s*.
- Using the LHC beam as a driver, *TeV* electron beams are possible.

E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008).

Possible physics experiments I

- Use of electron beam for test-beam programmes.
  - Test-beam infrastructure for detector characterisation often over-subscribed.
  - Accelerator test facility. Also not many world-wide.
  - Characteristics
    - Variation of energy.
    - Provide pure electron beam.
    - Short bunches.
- Fixed-target experiments using electron beams, e.g. deep inelastic electron−proton/*A* scattering.
  - Measurements at high *x*, momentum fraction of struck parton in the proton, with higher statistics than previous experiments. Valuable for LHC physics.
  - Polarised beams and spin structure of the nucleon. The “proton spin crisis/puzzle” is a still a big unresolved issue.
  - Use of different targets and understanding the physics of that (Stodolsky).

Possible physics experiments II

- **Search for dark photons à la NA64**
  - Consider beam-dump and counting experiments.
- High energy electron−proton collider
  - A low-luminosity LHeC-type experiment: *~50 GeV* beam within *50−100 m* of plasma driven by SPS protons; low luminosity, but much more compact.
  - A very high energy electron−proton (VHEeP) collider with $\sqrt{s}$ ***= 9 TeV,*** ×*30* higher than HERA. Developing physics programme*.

This is not a definitive list, but a quick brainstorm.

Demonstrate that these experiments probe exciting areas of physics and will really profit from an AWAKE-like beam.

*A. Caldwell and M. Wing, Eur. Phys. J. **C 76** (2016) 463

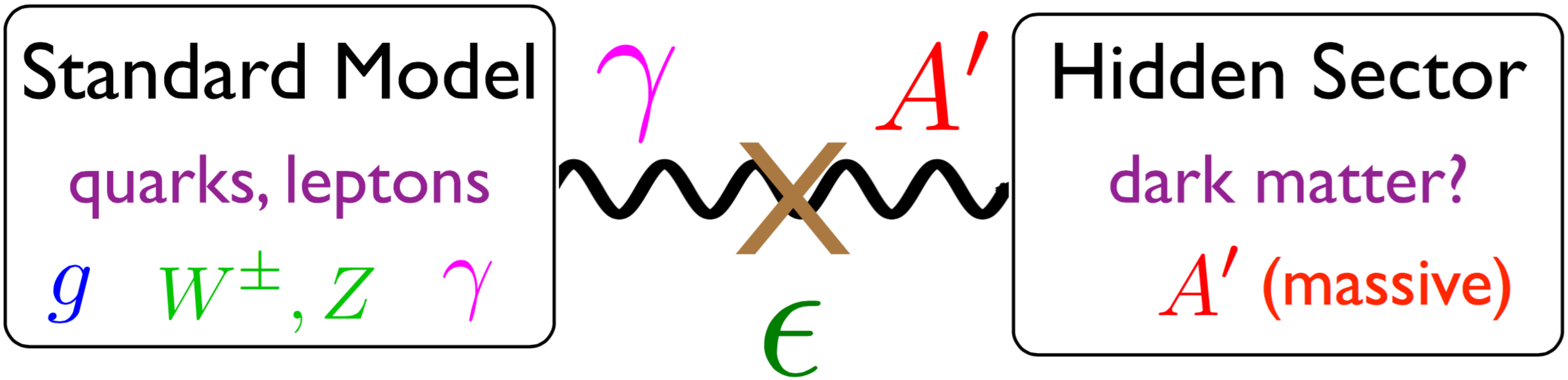
The hidden / dark sector

- Baryonic (ordinary) matter constitutes ~*5%* of known matter.
  - What is the nature of dark matter ? Why can we not see the dominant constituent of the Universe ?
- LHC Run 1 (and previous high energy colliders) have found no dark matter candidates so far.
- LHC Run 2 to continue that search looking for heavy new particles such as those within supersymmetry.
- Also direct detection experiments looking for recoil from WIMPs
- There are models which postulate light (*GeV* and below) new particles which could be candidates for dark matter.
- There could be a dark sector which couples to ordinary matter via gravity and possibly other very weak forces.
- Could e.g. explain $g-2$ anomaly between measurement and the Standard Model.

Dark photons

A light vector boson, the “dark photon”, *A′*, results from a spontaneously broken new gauge symmetry, $U(1)_D$.

The *A′* kinetically mixes with the photon and couples primarily to the electromagnetic current with strength, εe

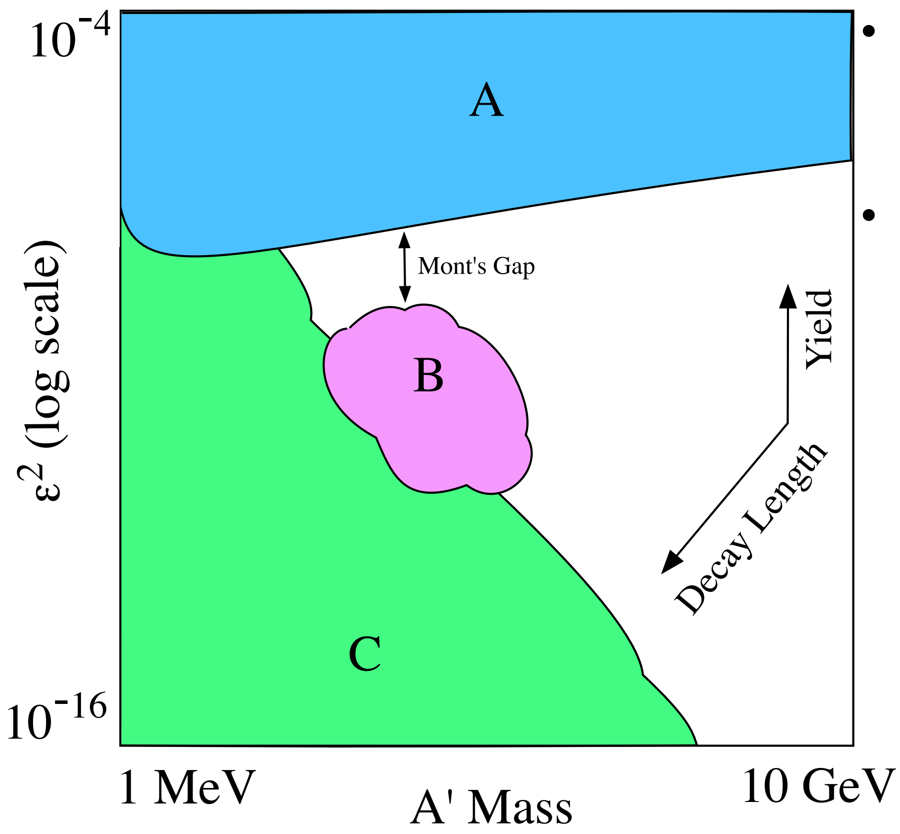


$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

Growing field of experiments with many running or starting or proposed at JLab, SLAC, INFN, Mainz, etc.

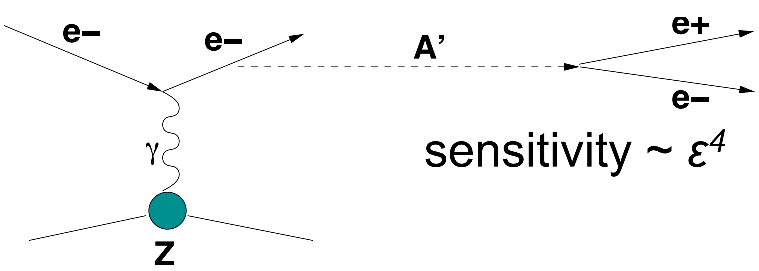
Search for dark photons

- Several ways to look for dark photons:
  - A: bump-hunting, e.g. $e^+e^- \rightarrow \gamma A'$
  - B: displaced vertices, short decay lengths
  - C: displaced vertices, long decay lengths

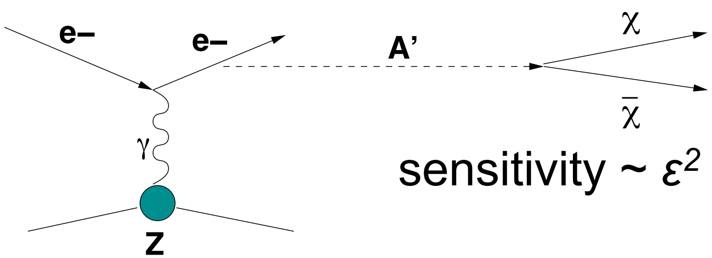


J. Alexander et al., arXiv:1608.08632

- Search for dark photons, *A′*, up to (and beyond) *GeV* mass scale via their production in a light-shining-through-a-wall type experiment.
- Use high energy electrons for beam-dump and/or fixed-target experiments.



sensitivity ~ ε^4



sensitivity ~ ε^2

NA64 experimental programme

NA64 have put forward a strong physics case to investigate the dark sector.

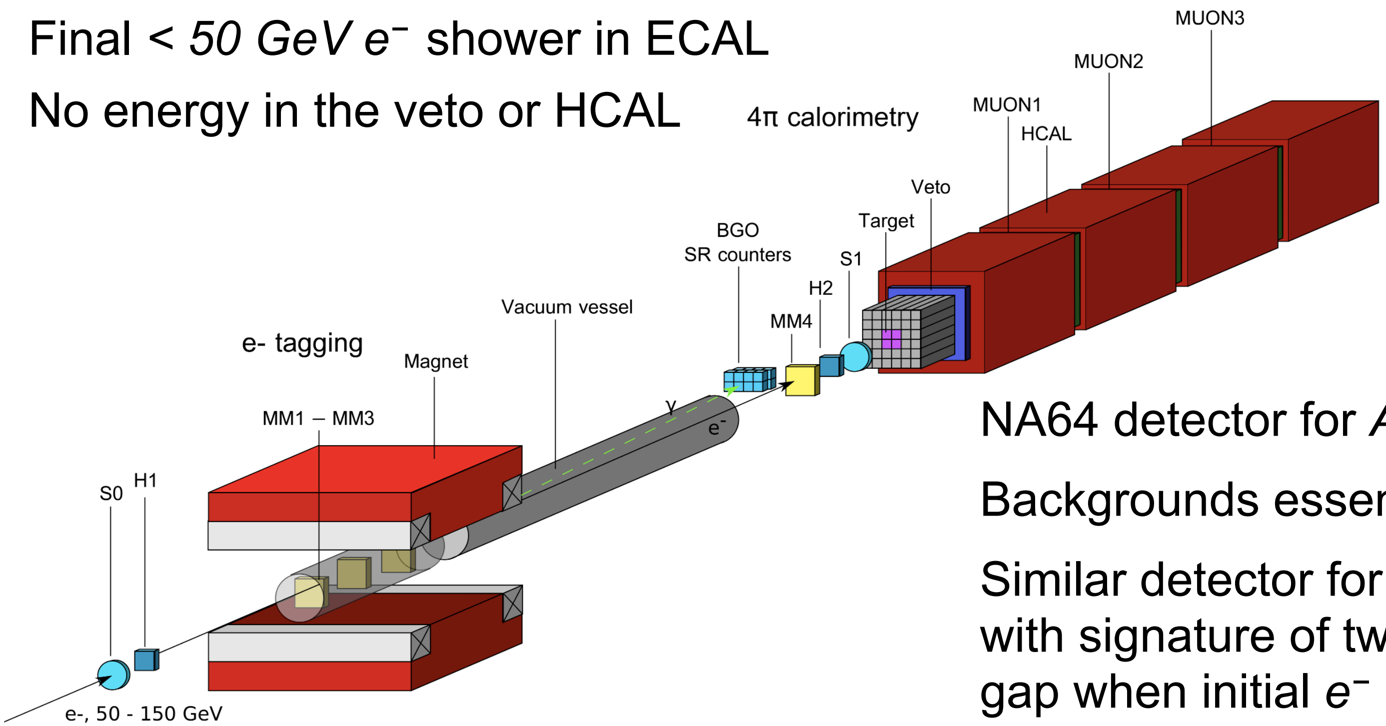
See various papers/proposals from them.

Initial run in SPS beam focusing on $A' \rightarrow$ *invisible* channel.

Future programme measuring $A' \rightarrow e^+ e^-$ channel.

Signature:

- Initial *100 GeV* e^- track
- Final < *50 GeV* e^- shower in ECAL
- No energy in the veto or HCAL



NA64 detector for $A' \rightarrow$ *invisible* channel.

Backgrounds essentially zero.

Similar detector for $A' \rightarrow e^+ e^-$ channel with signature of two EM showers after gap when initial e^- hits target.

Electrons on target

NA64 will receive about 10^6 $e^-/spill$ or 2×10^5 e^-/s from SPS secondary beam

➡ $N_e \sim 10^{12}$ e^- for 3 months running.

AWAKE-like beam with bunches of 10^9 e^- every (SPS cycle time of) ~ *5 s* or 2×10^8 e^-/s *(1000* × higher than NA64/SPS secondary beam*)*

➡ $N_e \sim 10^{15}$ e^- for 3 months running.

Will assume that an AWAKE-like beam could provide an **effective upgrade** to the NA64 experiment, increasing the intensity by a factor of *1000*.

Different beam energies or higher intensities (e.g. bunch charge, SPS cycle time) may be possible, but are not considered in this talk.

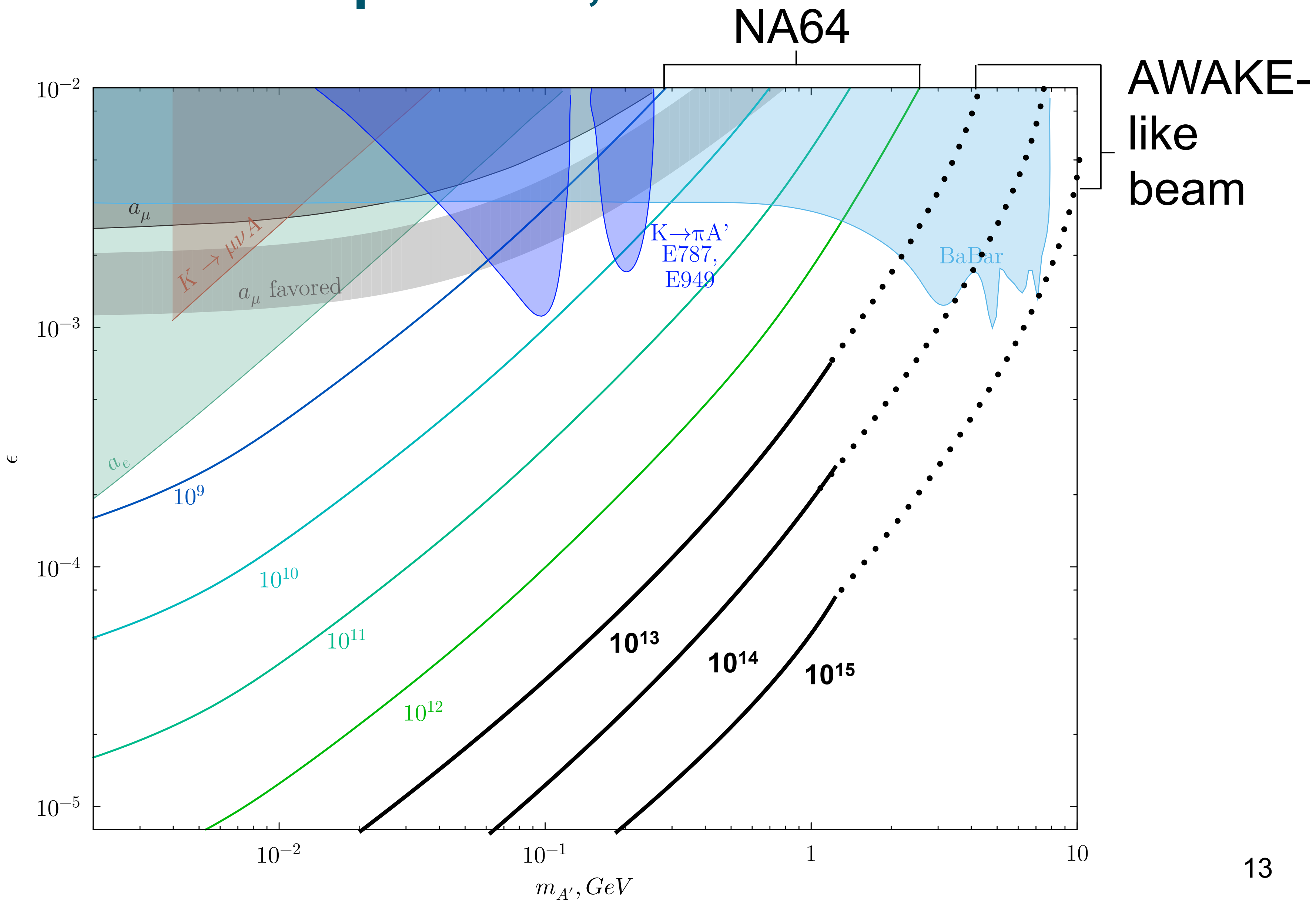
Sensitivity with increased electrons on target

Have taken plots of mixing strength, *ε,* versus mass, $m_{A'}$, from NA64 studies/proposals and added curves "by hand" to show increased sensitivity.

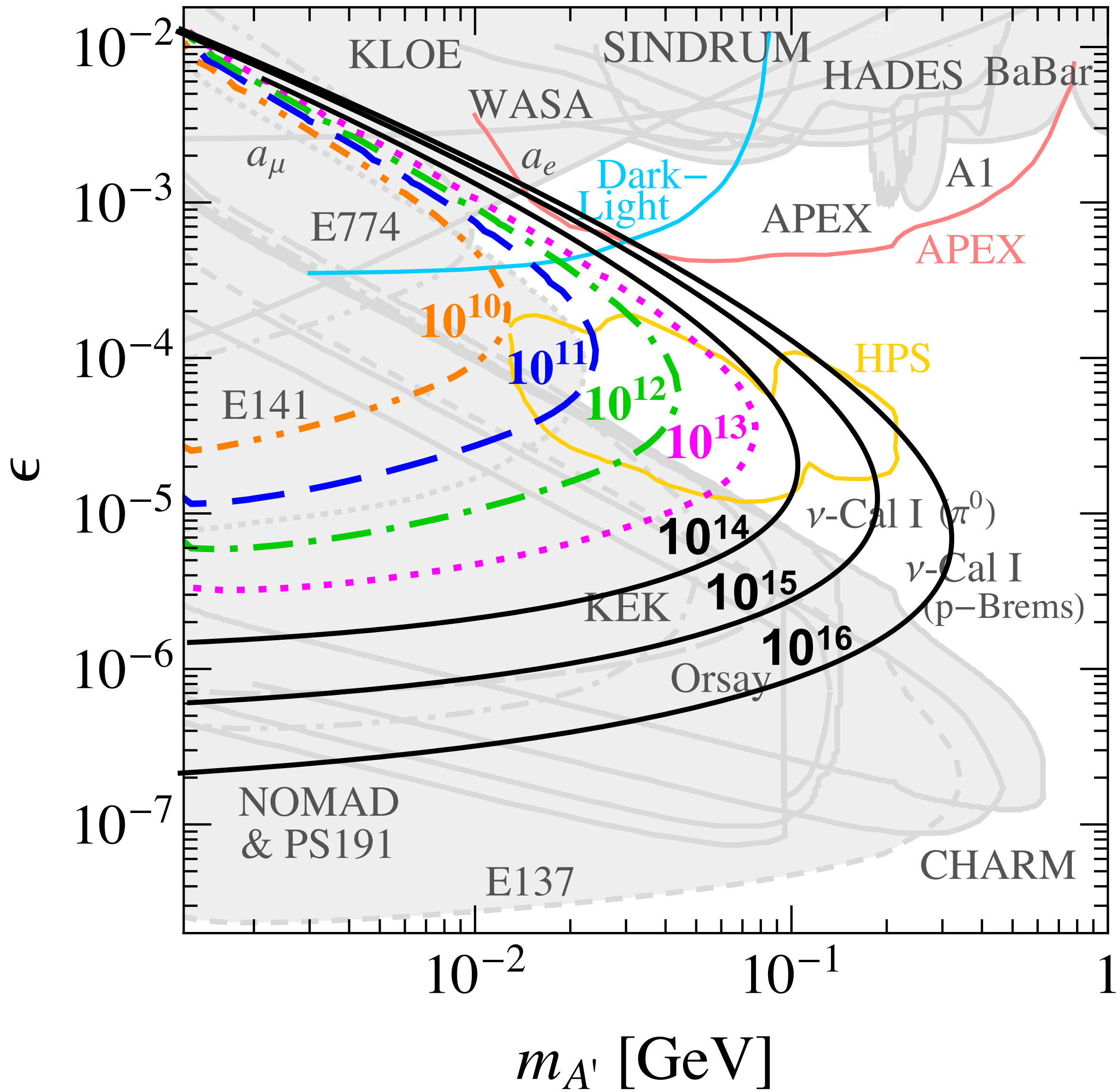
- Considered $A' \rightarrow e^+ e^-$ and $A' \rightarrow$ *invisible* channels.
- In general, but certainly at high $m_{A'}$ (> *1 GeV*) need more detailed calculations (developed in S.N. Gninenko et al., arXiv:1604.08432).
- More careful study of optimal beam energy needed.
- Evaluation of backgrounds needed; currently assume background-free for AWAKE-like beam.
- More careful study of possible detector configurations.
- Could consider other channels, e.g. $A' \rightarrow \mu^+ \mu^-$.
- For a beam-dump experiment ($A' \rightarrow e^+ e^-$), high intensities possible; for a counting experiment ($A' \rightarrow$ *invisible*), need to cope/count high number of electrons on target.

Results shown here should be considered as indicative.

Limits on dark photons, *A'* → *invisible* channel



Limits on dark photons, $A' \rightarrow e^+ e^-$



For $10^{10} - 10^{13}$ electrons on target with NA64.

For $10^{14} - 10^{16}$ electrons on target with AWAKE-like beam.

As proposed by NA64 group:

- extend into region not covered by current limits.
- similar to and complement other future experiments.

Using an AWAKE-like beam would extend sensitivity further around $\varepsilon \sim 10^{-5}$ beyond any current or planned experiment.

Relation to EuPRAXIA I

For fixed-target electron−proton/*A* experiments:

- Beam energy is low, so Q^2 is low, e.g. $E_e = 5$ *GeV* gives $\sqrt{s} \sim 3$ *GeV and* $Q^2 < 10$ *GeV*^{2}.
- Can still go to high x and use different targets.
- Spin physics may still be interesting.
- Would need to be assessed: survey of previous experiments, conditions needed, design, potential for new experiments and **physics motivation**.

Relation to EuPRAXIA II

On the search for dark photons:

- Again the beam energy is lower than for NA64 and application of AWAKE scheme, but:
  - Looking for sub-GeV particles;
  - Several other projects, e.g. JLab, Mainz, etc., using/considering low energy electron beams;
  - Need to assess optimal energy and competitiveness with other experiments.
- The bunch charge is similar to that for AWAKE scheme and repetition rate is higher.
  - More electrons on target means higher sensitivity to new physics.
  - 200×10^6 e^- at *10 Hz* is 2×10^9 e^-/s, a factor of *10* higher than default AWAKE scheme.
  - 600×10^6 e^- at *100 Hz* is 6×10^{10} e^-/s, a factor of *300* higher than default AWAKE scheme.
  - For a beam-dump experiment, this higher rate may be manageable; for a fixed-target experiment, more challenging to count and measure incoming electrons.
- Work and studies needed.

Summary

- Plasma wakefield acceleration is a promising scheme for production of high energy electron beams.
- Considering HEP possibilities using AWAKE scheme and CERN infrastructure.
- Some of the ideas may be applicable to EuPRAXIA and a lower-energy electron beam.
  - Experiments in deep inelastic scattering are possible; physics case needs to be developed.
  - Fixed-target/beam-dump experiments in particular those sensitive to dark photons have a strong physics case; studies needed.
- Ideas should have a strong particle physics case and be realisable; certainly the dark photon search fits that.
- Work and studies are needed to develop these possibilities.

Back-up

From: arXiv:1608.08632

TABLE I: Summary of dark photon experiments.

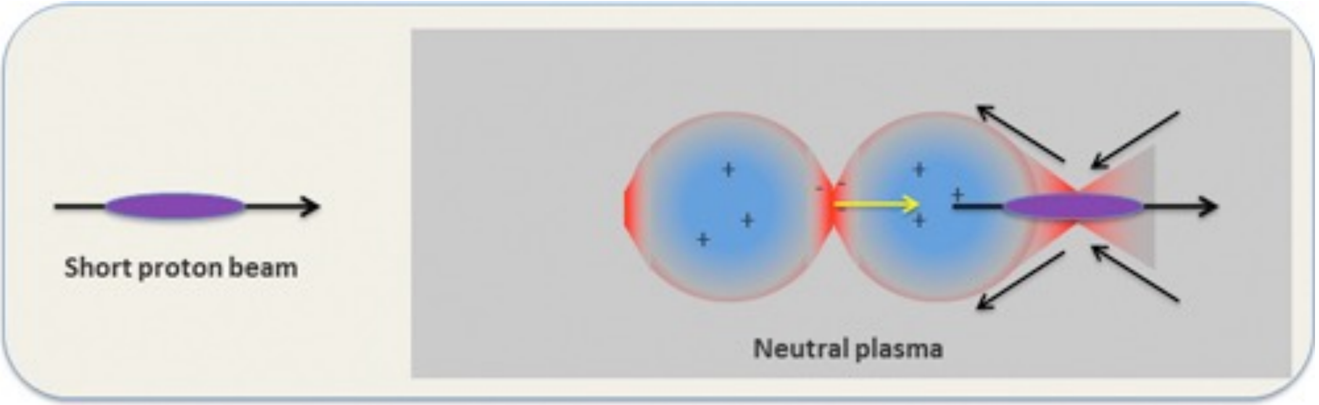
Experiment	Lab	Production	Detection	Vertex	Mass(MeV)	Mass Res. (MeV)	Beam	Ebeam (GeV)	Ibeam or Lumi	Machine	1st Run	Next Run
APEX	JLab	e-brem	$\ell^+\ell^-$	no	$65 - 600$	0.5%	e^-	1.1–4.5	150 μA	CEBAF(A)	2010	2018
A1	Mainz	e-brem	e^+e^-	no	$40 - 300$	?	e^-	0.2–0.9	140 μA	MAMI	2011	–
HPS	JLab	e-brem	e^+e^-	yes	$20 - 200$	1–2	e^-	1–6	50–500 nA	CEBAF(B)	2015	2018
DarkLight	JLab	e-brem	e^+e^-	no	< 80	?	e^-	0.1	10 mA	LERF	2016	2018
MAGIX	Mainz	e-brem	e^+e^-	no	$10 - 60$	?	e^-	0.155	1 mA	MESA	2020	–
NA64	CERN	e-brem	e^+e^-	no	$1 - 50$	?	e^-	100	2×10^{11} EOT/yr	SPS	2017	2022
Super-HPS	SLAC	e-brem	vis	yes	< 500	?	e^-	$4 - 8$	1 μA	DASEL	?	?
(TBD)	Cornell	e-brem	e^+e^-	?	< 100	?	e^-	0.1-0.3	100 mA	CBETA	?	?
VEPP3	Budker	annih	invis	no	$5 - 22$	1	e^+	0.500	10^{33} cm^{-2}s^{-1}	VEPP3	2019	?
PADME	Frascati	annih	invis	no	$1 - 24$	$2 - 5$	e^+	0.550	$\leq 10^{14}$ e^+OT/y	Linac	2018	?
MMAPS	Cornell	annih	invis	no	$20 - 78$	$1 - 6$	e^+	6.0	10^{34} cm^{-2}s^{-1}	Synchr	?	?
KLOE 2	Frascati	several	vis/invis	no	< 1.1 GeV	1.5	e^+e^-	0.51	2×10^{32} cm^{-2}s^{-1}	DAϕNE	2014	-
Belle II	KEK	several	vis/invis	no	$\lesssim 10$ GeV	$1 - 5$	e^+e^-	4×7	$1 \sim 10$ ab^{-1}/y	Super-KEKB	2018	-
SeaQuest	FNAL	several	$\mu^+\mu^-$	yes	$\lesssim 10$ GeV	$3 - 6\%$	p	120	10^{18} POT/y	MI	2017	2020
SHIP	CERN	several	vis	yes	$\lesssim 10$ GeV	$1 - 2$	p	400	2×10^{20} POT/5y	SPS	2026	-
LHCb	CERN	several	$\ell^+\ell^-$	yes	$\lesssim 40$ GeV	~ 4	pp	6500	~ 10 fb^{-1}/y	LHC	2010	2015

Plasma wakefield acceleration

Accelerators using RF cavities limited to *~100 MV/m*; high energies ⇒ long accelerators.

Gradients in plasma wakefield acceleration of ***~100 GV/m*** measured.

Proton-driven plasma wakefield acceleration*



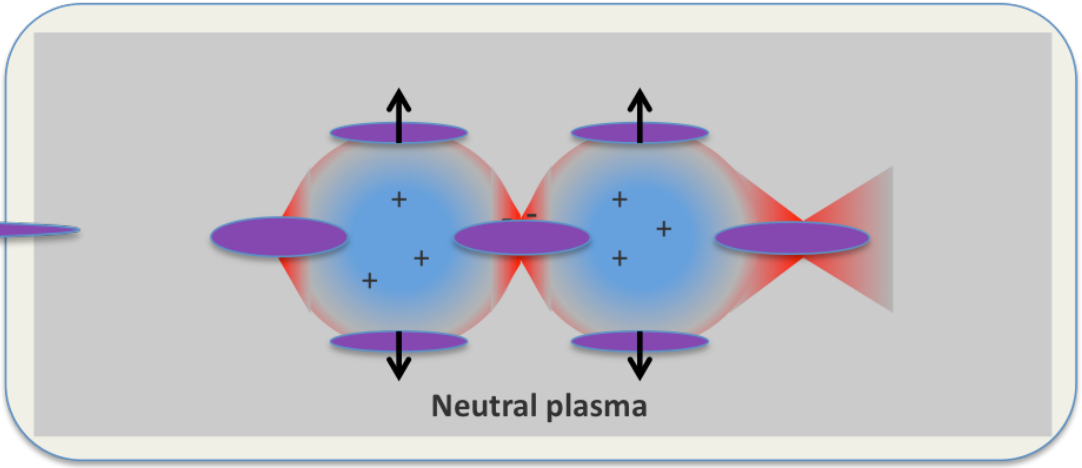
- Electrons 'sucked in' by proton bunch
- Continue across axis creating depletion region
- Transverse electric fields focus witness bunch

- Theory and simulation tell us that with CERN proton beams, can get *GV/m* gradients.
- Experiment, AWAKE, at CERN to demonstrate proton-driven plasma wakefield acceleration for this first time.
    - Learn about characteristics of plasma wakefields.
    - Understand process of accelerating electrons in wakes.
    - This will inform future possibilities which we, however, can/should think of now.

* A. Caldwell *et al*., Nature Physics **5** (2009) 363.

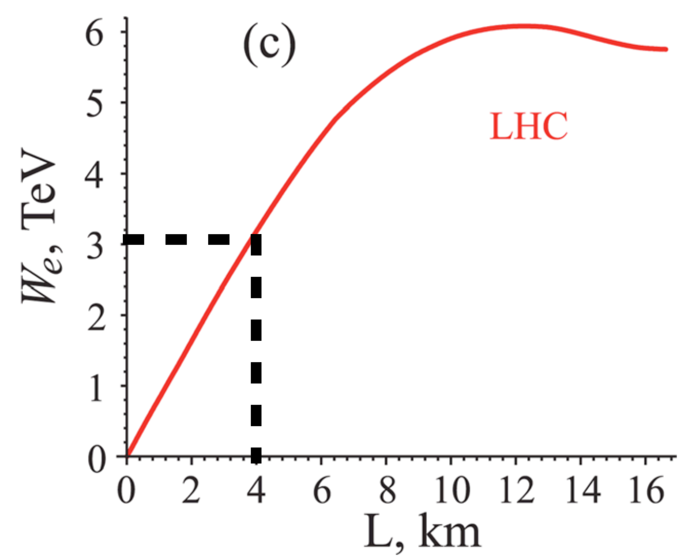
Plasma wakefield accelerator (AWAKE scheme)

Long proton beam



Self-modulated driver beam

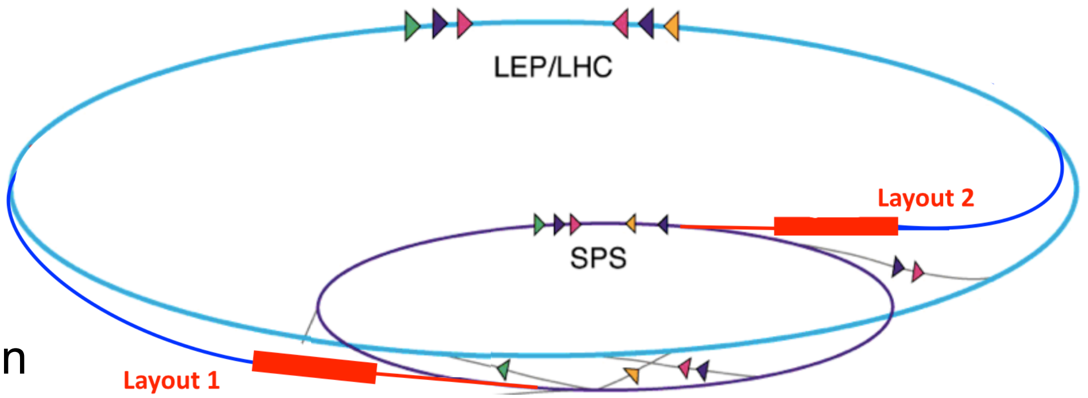
- Long beam modulated into micro-bunches which constructively reinforce to give large wakefields.
- Self-modulation instability allows **current beams to be used**, as in AWAKE experiment at CERN.
- With high accelerating gradients, can have
  - Shorter colliders for same energy
  - Higher energy
- Using the LHC beam can accelerate electrons up to *6 TeV* over a reasonable distance.
- We choose E_e = *3 TeV* as a baseline for a new collider with E_P = *7 TeV* ⇒ $\sqrt{s}$ **= 9 TeV**.
  - Centre of mass energy ×30 higher than HERA.



A. Caldwell & K. Lotov, Phys. Plasmas **18** (2011) 103101

High energy electron−proton collisions

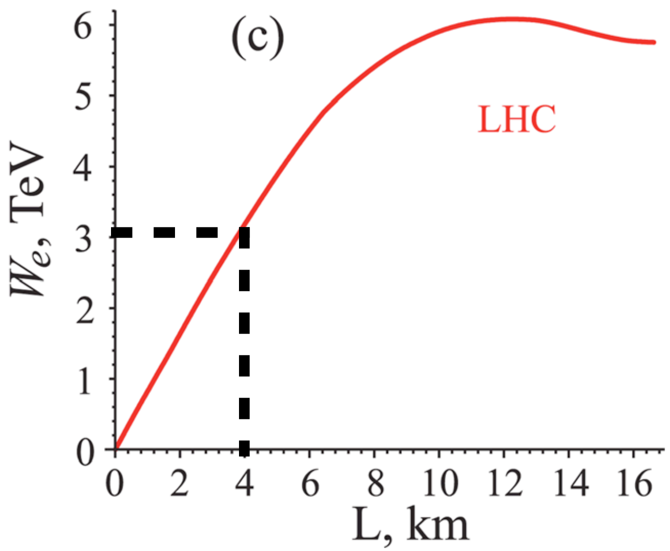
- Consider high energy *ep* collider with E_e up to *O(50 GeV),* colliding with LHC proton *TeV* bunch, e.g. $E_e = 10$ *GeV*, $E_p = 7$ *TeV*, $\sqrt{s} = 530$ *GeV.*
- Create ~*50 GeV* beam within *50−100 m* of plasma driven by SPS protons and have an LHeC-type experiment.
- Clear difference is that luminosity* currently expected to be lower ~10^{30} $cm^{-2}s^{-1}$.



- Any such experiment would have a different focus to LHeC.
  - Investigate physics at low Bjorken *x*, e.g. saturation.
  - Parton densities, diffraction, jets, etc..
  - *eA* as well as *ep* physics.
- Opportunity for further studies to consider the design of a collider using this plasma wakefield acceleration scheme and leading to an experiment in a new kinematic regime.

*G. Xia et al., Nucl. Instrum. Meth. **A 740** (2014) 173.

Very high energy electron−proton collisions, VHEeP*

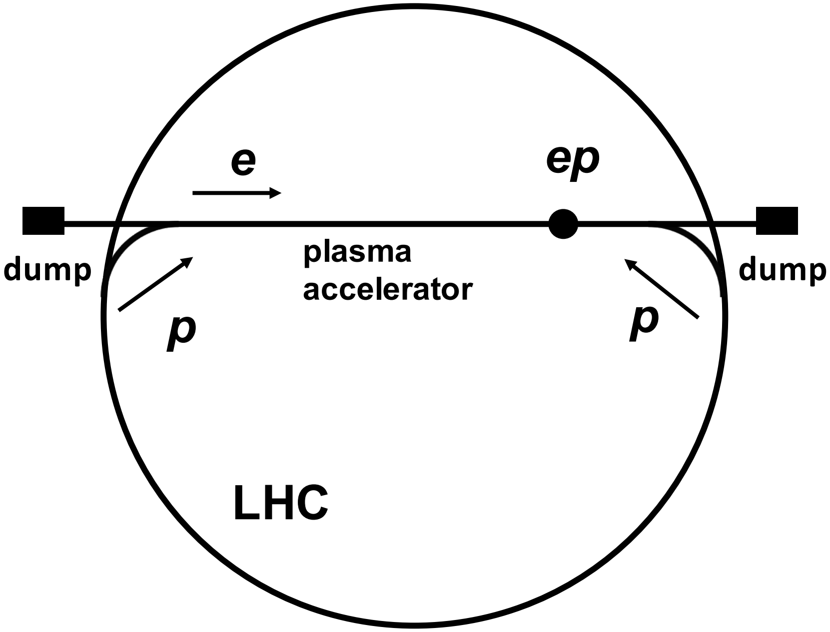


A. Caldwell & K. Lotov, Phys. Plasmas **18** (2011) 103101

• What about very high energies in a completely new kinematic regime ?

• Choose E_e = *3 TeV* as a baseline for a new collider with E_P = *7 TeV* ⇒ **$\sqrt{s}$ = *9 TeV***. Can vary.

- Centre-of-mass energy ×30 higher than HERA.
- Reach in (high) Q^2 and (low) Bjorken *x* extended by ×1000 compared to HERA.

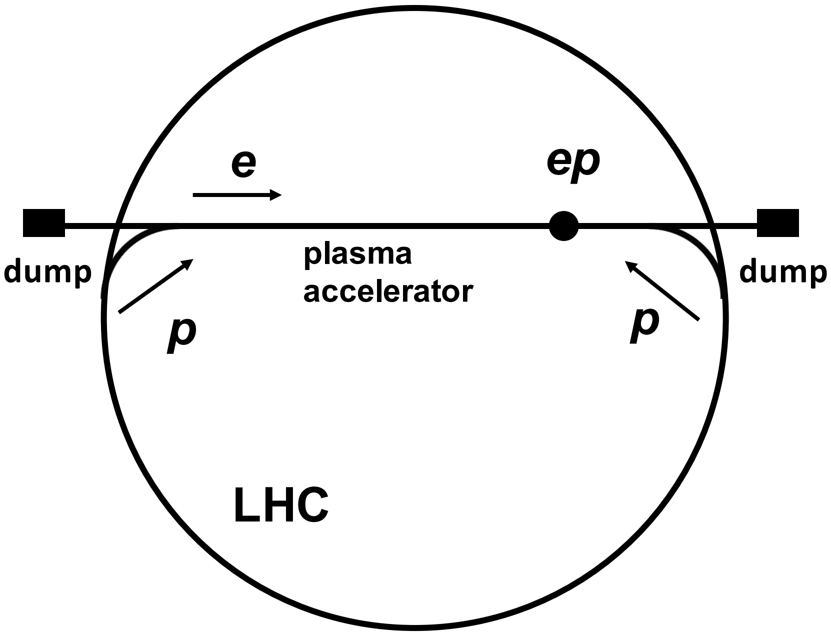


- Overall (simple) layout using current infrastructure.
- One proton beam used for electron acceleration to then collide with other proton beam
- Luminosity ~ $10^{28} - 10^{29}$ cm^{-2}s^{-1} gives ~ 1 pb^{-1} per year

Physics case for very high energy, but moderate (*10−100 pb^{-1}*) luminosities.

*A. Caldwell and M. Wing, Eur. Phys. J. **C 76** (2016) 463

Plasma wakefield accelerator



- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable and can vary electron beam energy.
- What about luminosity ?

$$\mathcal{L} \sim \frac{f \cdot N_e \cdot N_P}{4\pi\,\sigma_x \cdot \sigma_y}$$
$$\sim 4 \times 10^{28}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

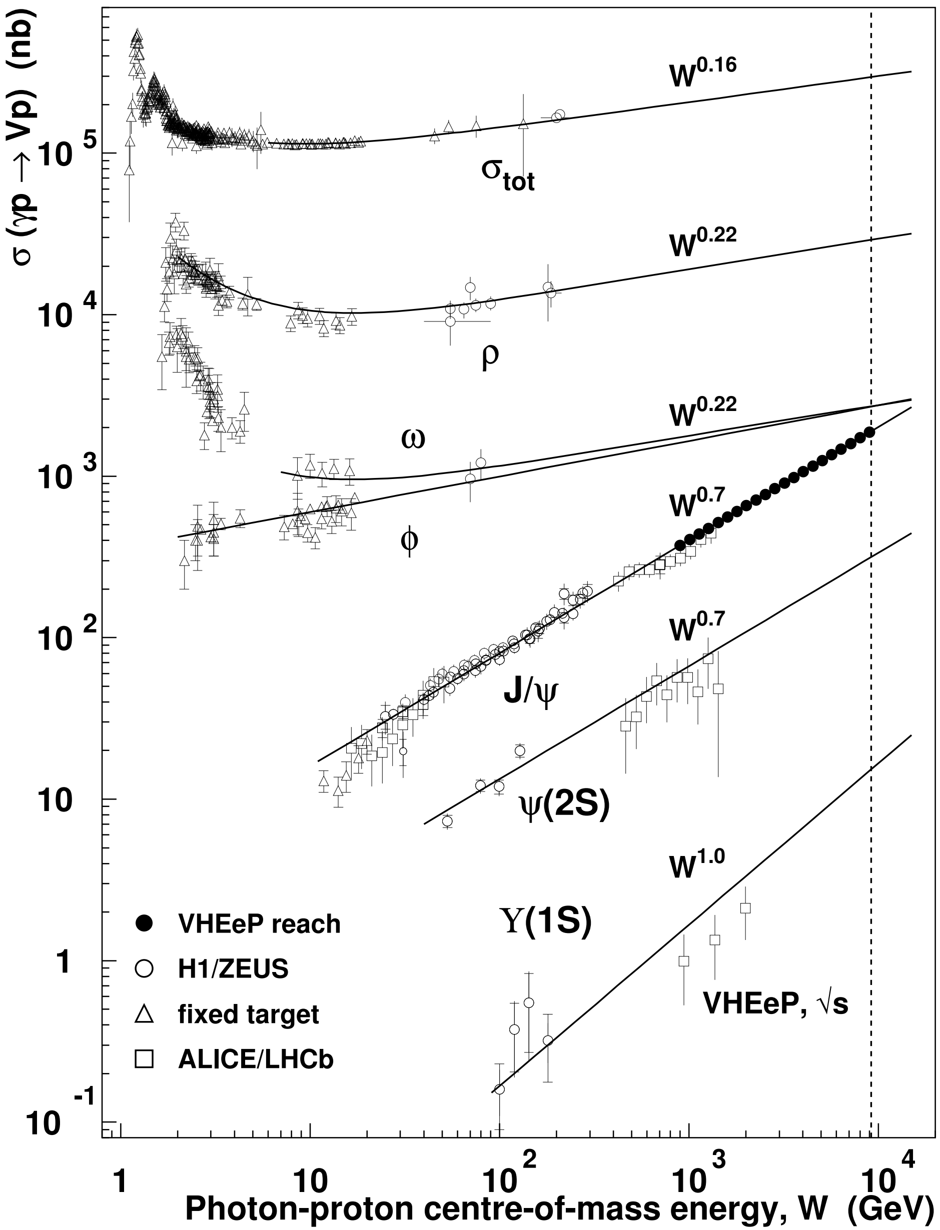
- Assume
  - *~3000* bunches every *30 mins*, gives *f ~ 2 Hz*.
  - $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
  - $\sigma \sim 4\ \mu m$

For few × 10^7 s, have $1\ pb^{-1}$ / year of running.

Other schemes to increase this value ?

Physics case for very high energy, but moderate (*10−100* pb^{-1}) luminosities.

Vector meson cross sections



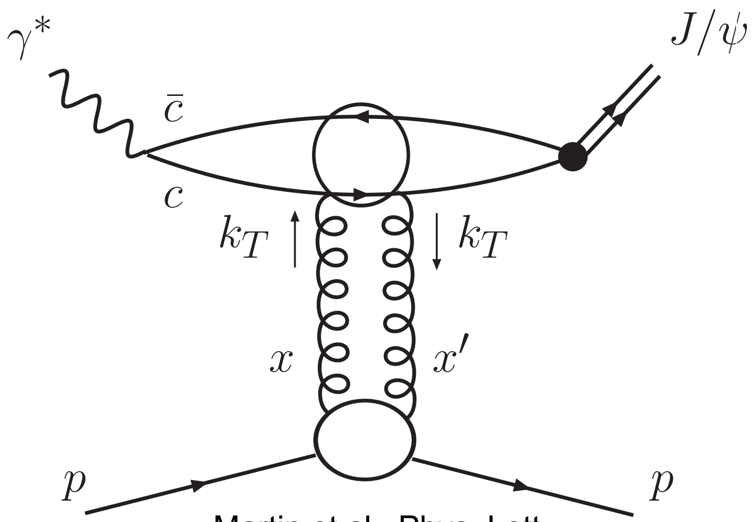
Strong rise with energy related to gluon density at low *x*.

Can measure all particles within the same experiment.

Comparison with fixed-target, HERA and LHCb data—large lever in energy.

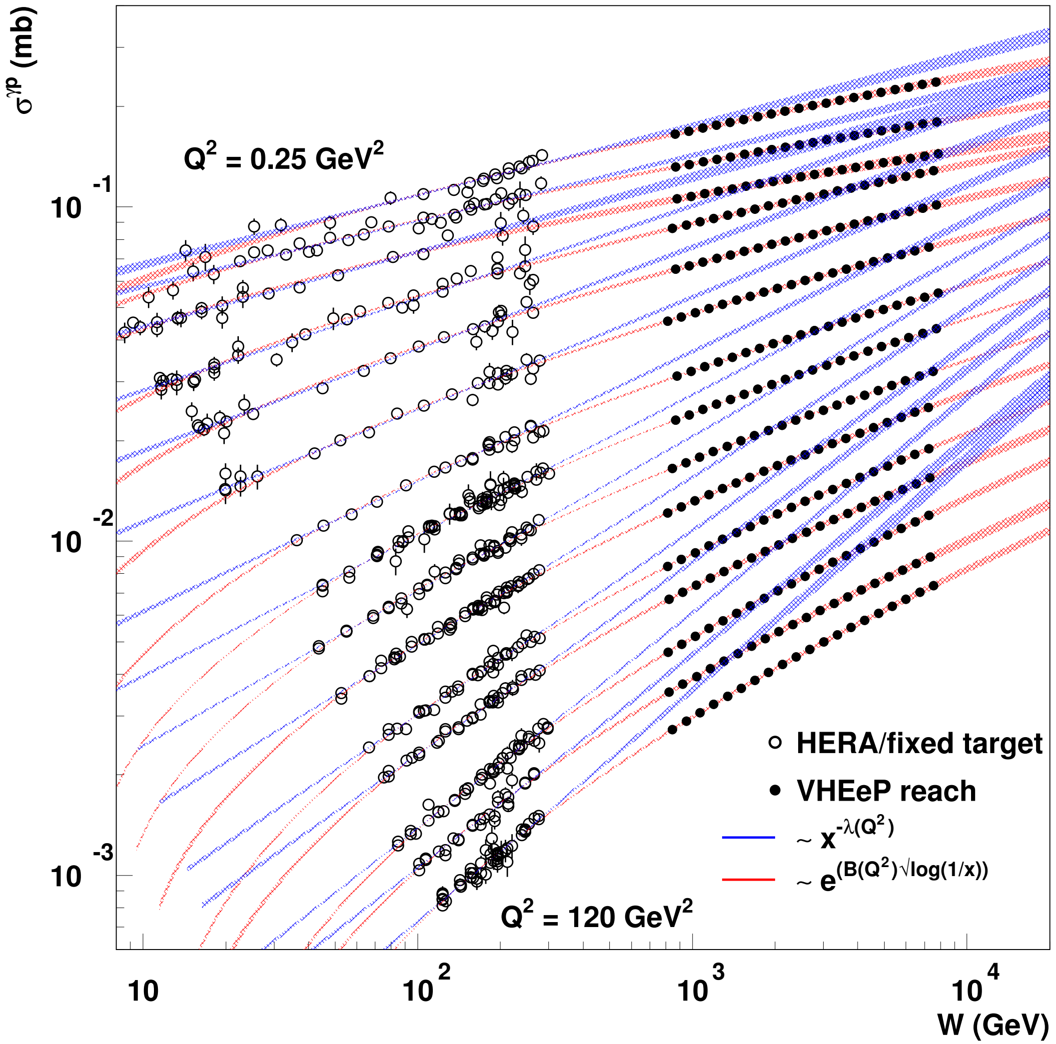
At VHEeP energies, *σ(J/ψ) > σ(φ)* !

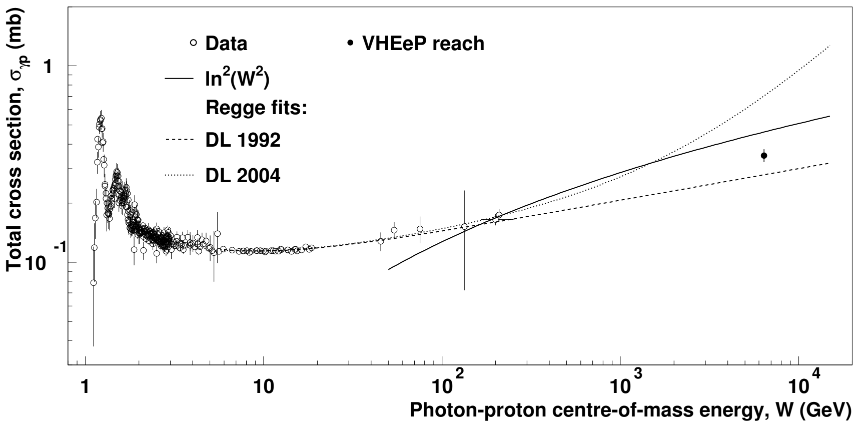
Onset of saturation ?



Martin et al., Phys. Lett. **B 662** (2008) 252

Very high energy electron–proton collisions, VHEeP





- Energy dependence of hadronic cross sections poorly understood.
  - Large lever arm at VHEeP.
  - Relation to cosmic-ray physics.
  - Onset of saturation ?
- **Explore a region where QCD is not at all understood.**
- Also strongly sensitive to leptoquarks and much else.

To organise a workshop to better understand the physics case and feasibility.

*A. Caldwell and M. Wing, Eur. Phys. J. **C 76** (2016) 463

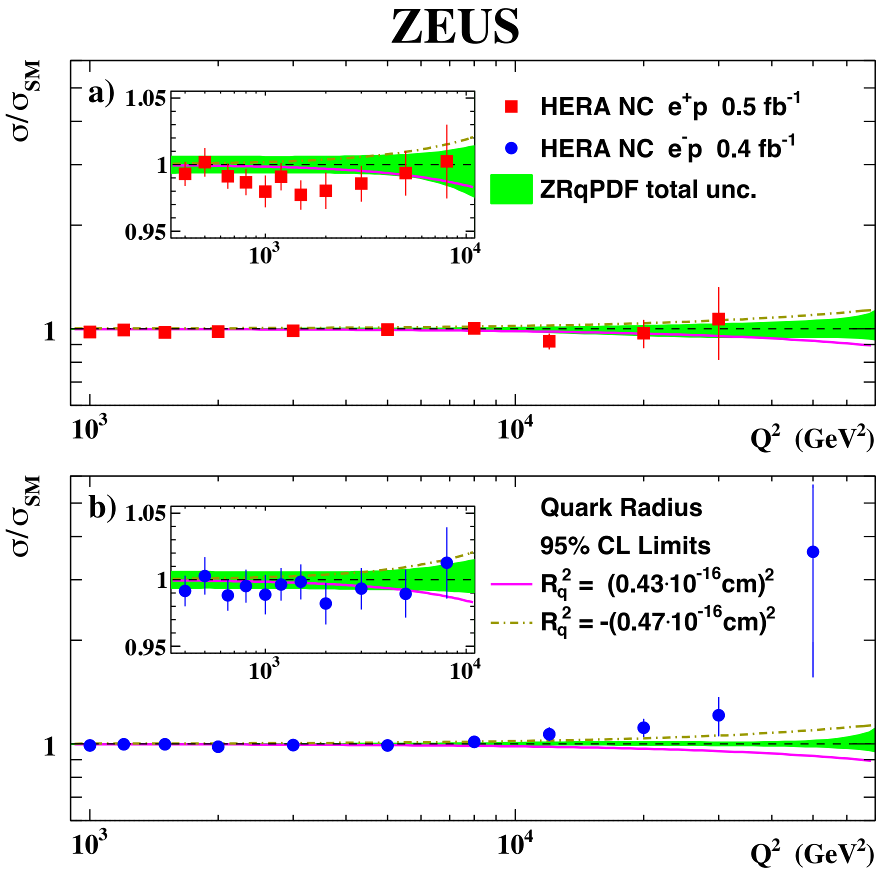
BSM: Quark substructure

Deviations of the theory from the data for inclusive cross sections could hint towards quark substructure.

Extraction of quark radius has been done

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1-\frac{R_e^2}{6}Q^2\right)^2\left(1-\frac{R_q^2}{6}Q^2\right)^2$$

Generate some "data" for VHEeP and look at sensitivity.

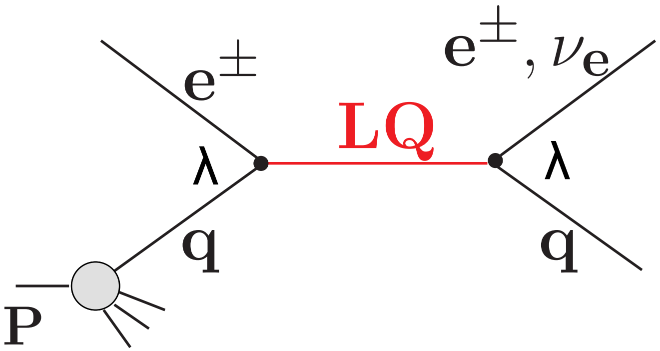


ZEUS Coll., DESY-16-035, accepted by Phys. Lett. B

Assuming the electron is point-like, HERA limit is $R_q < 4 \times 10^{-19}$ m

Assuming the electron is point-like, VHEeP limit is $R_q \lesssim 10^{-20}$ m

Leptoquark production

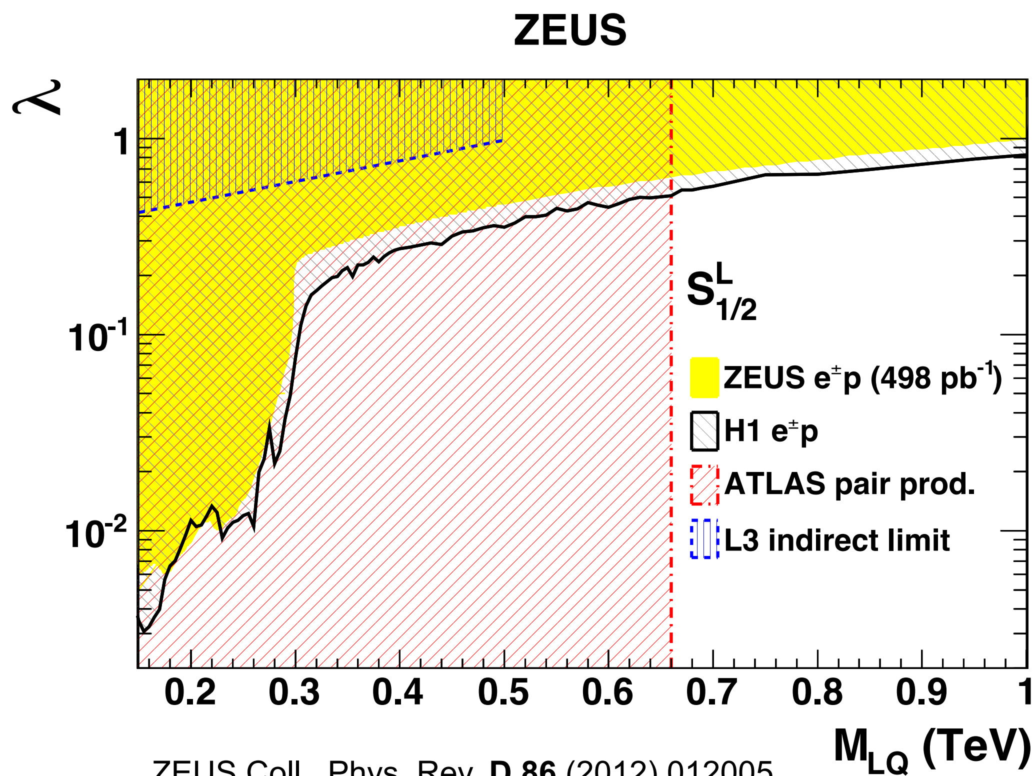


Electron−proton colliders are the ideal machine to look for leptoquarks.

s-channel resonance production possible up to $\sqrt{s}$.

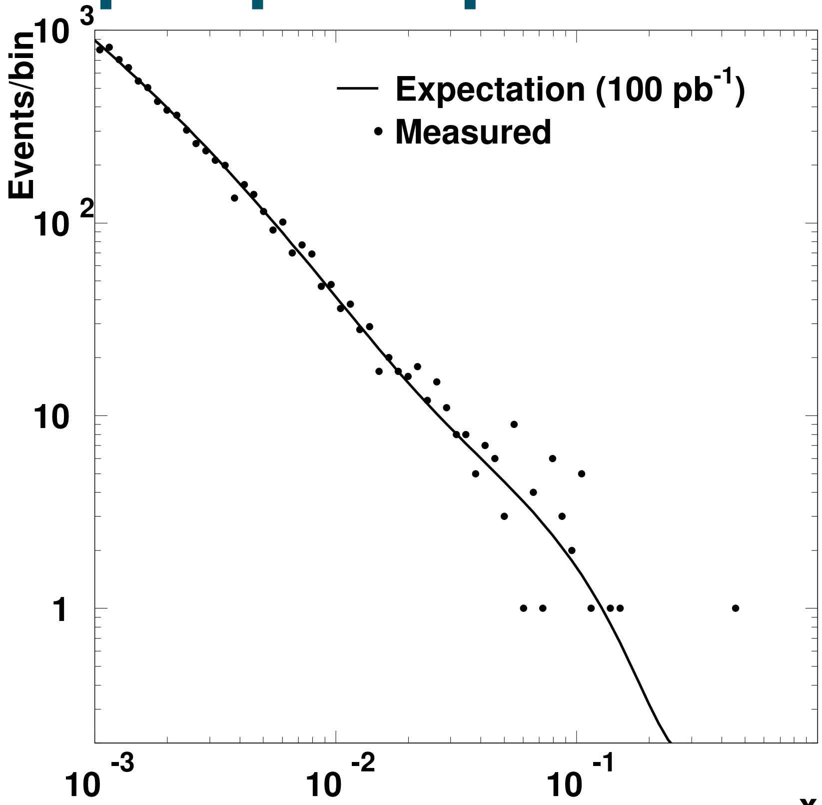
$$\sigma^{\mathrm{NWA}} = (J+1)\frac{\pi}{4s}\lambda^2\, q(x_0, M_{\mathrm{LQ}}^2)$$

Sensitivity depends mostly on $\sqrt{s}$ and VHEeP = 30 × HERA



ZEUS Coll., Phys. Rev. **D 86** (2012) 012005

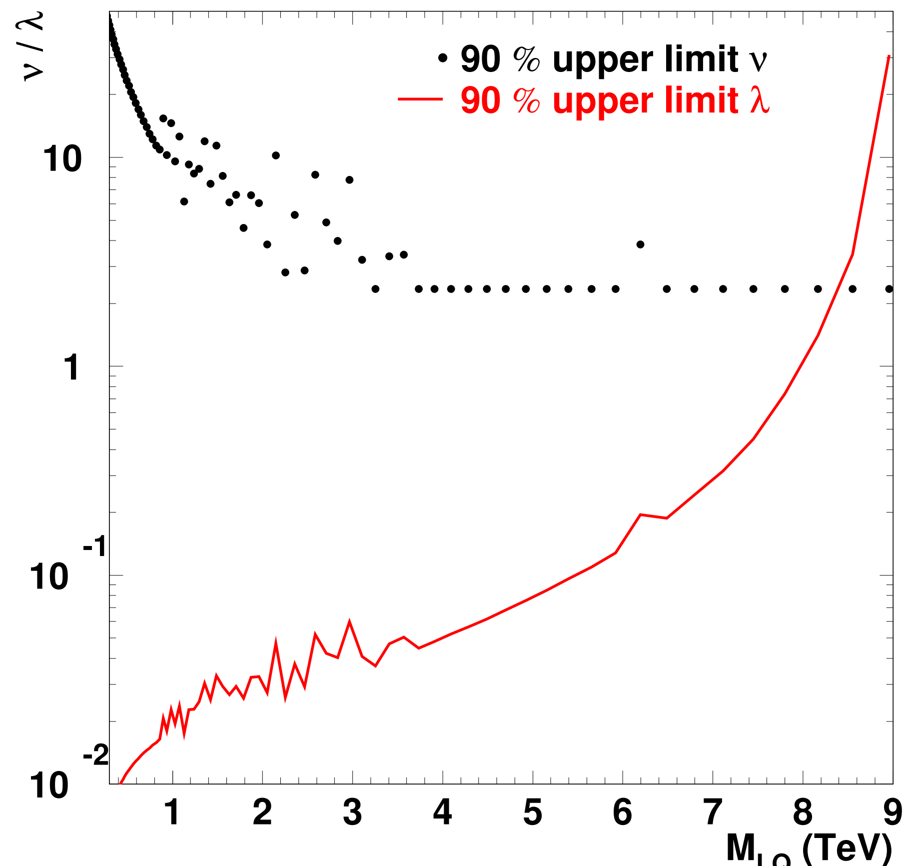
Leptoquark production at VHEeP



Assumed $L \sim 100\ pb^{-1}$

Required $Q^2 > 10{,}000\ GeV^2$ and $y > 0.1$

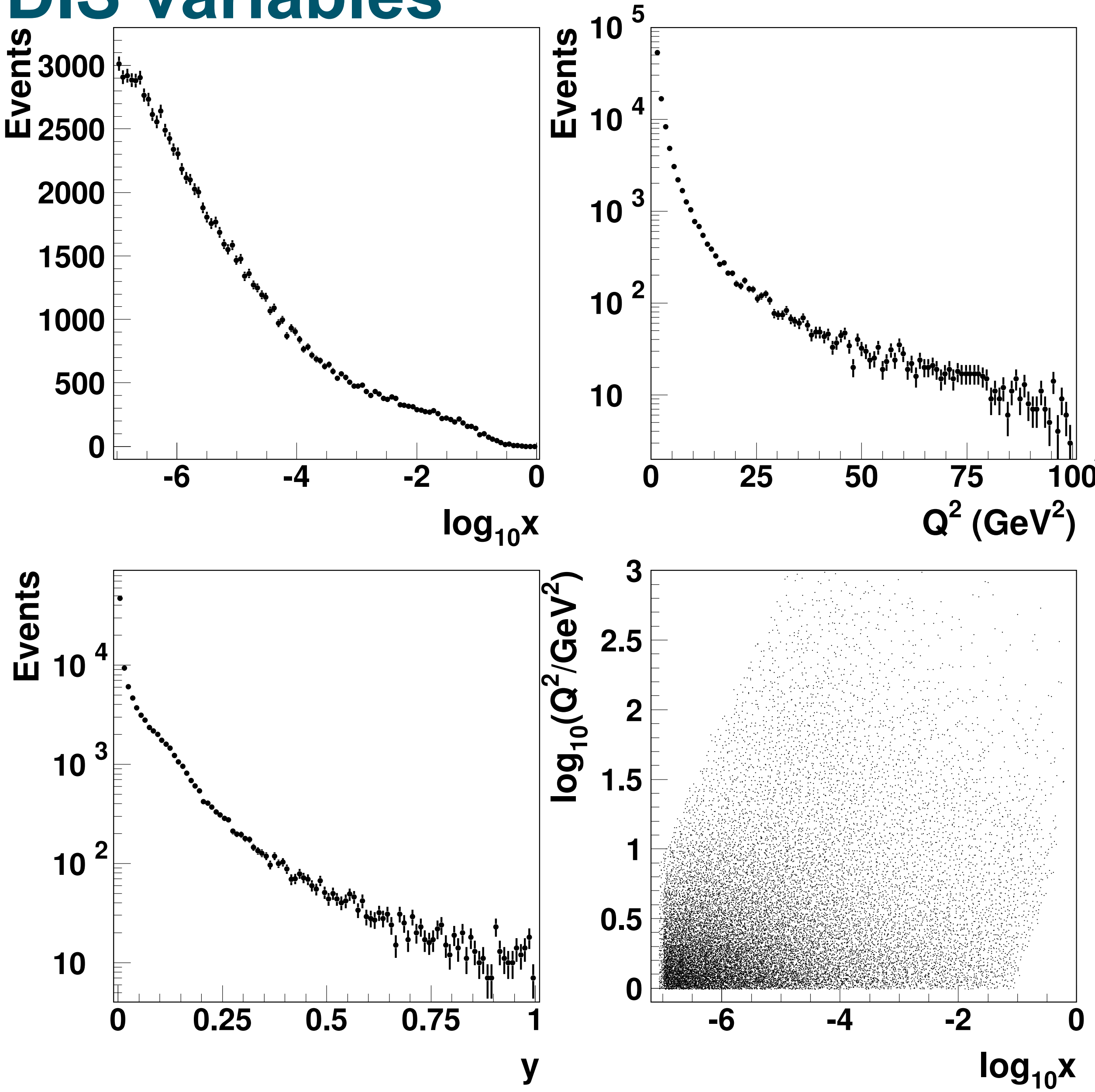
Generated “data” and Standard Model “prediction” using ARIADNE (no LQs).



Sensitivity up to kinematic limit, 9 TeV.

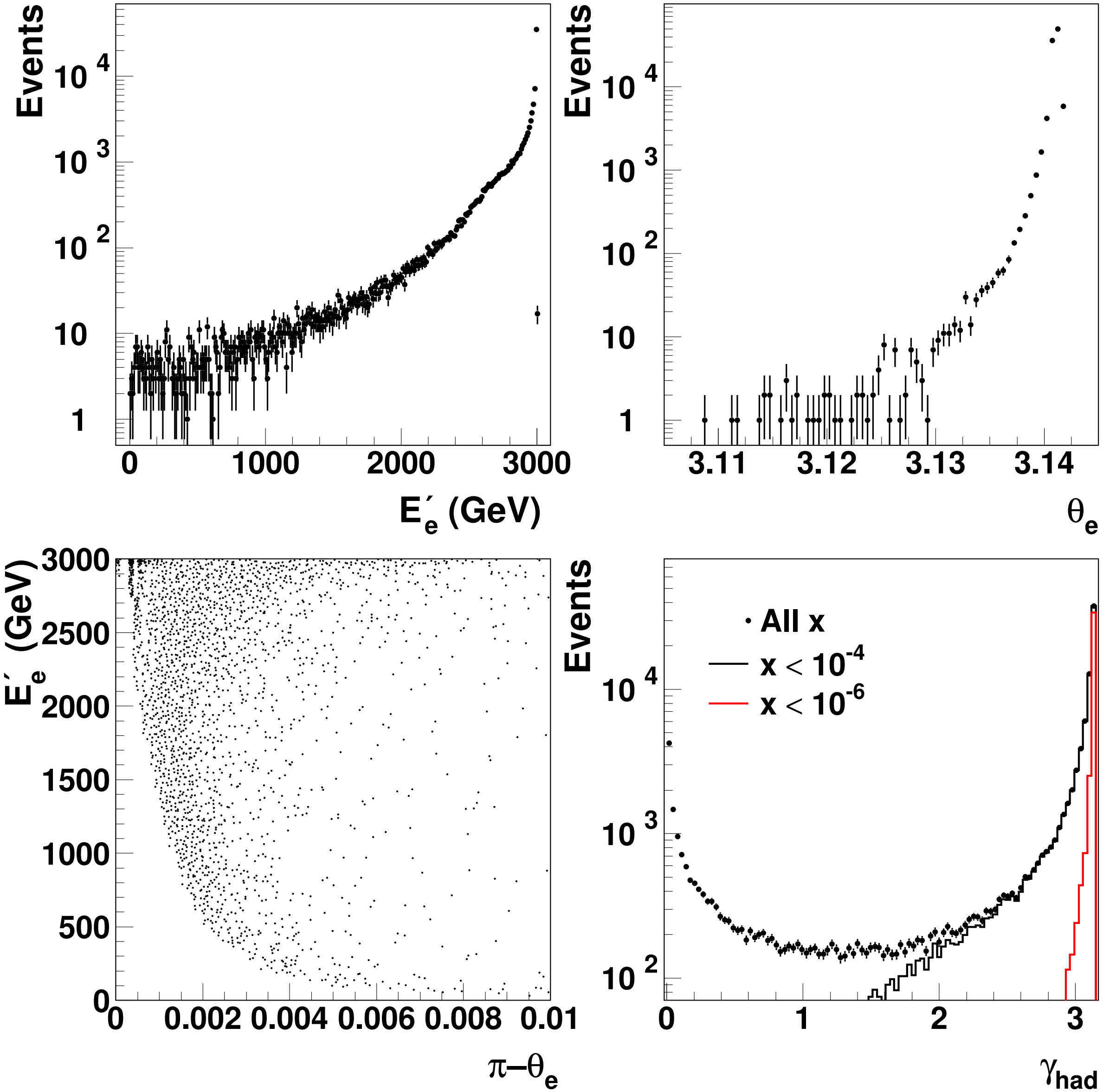
As expected, well beyond HERA limits and significantly beyond LHC limits and potential.

DIS variables



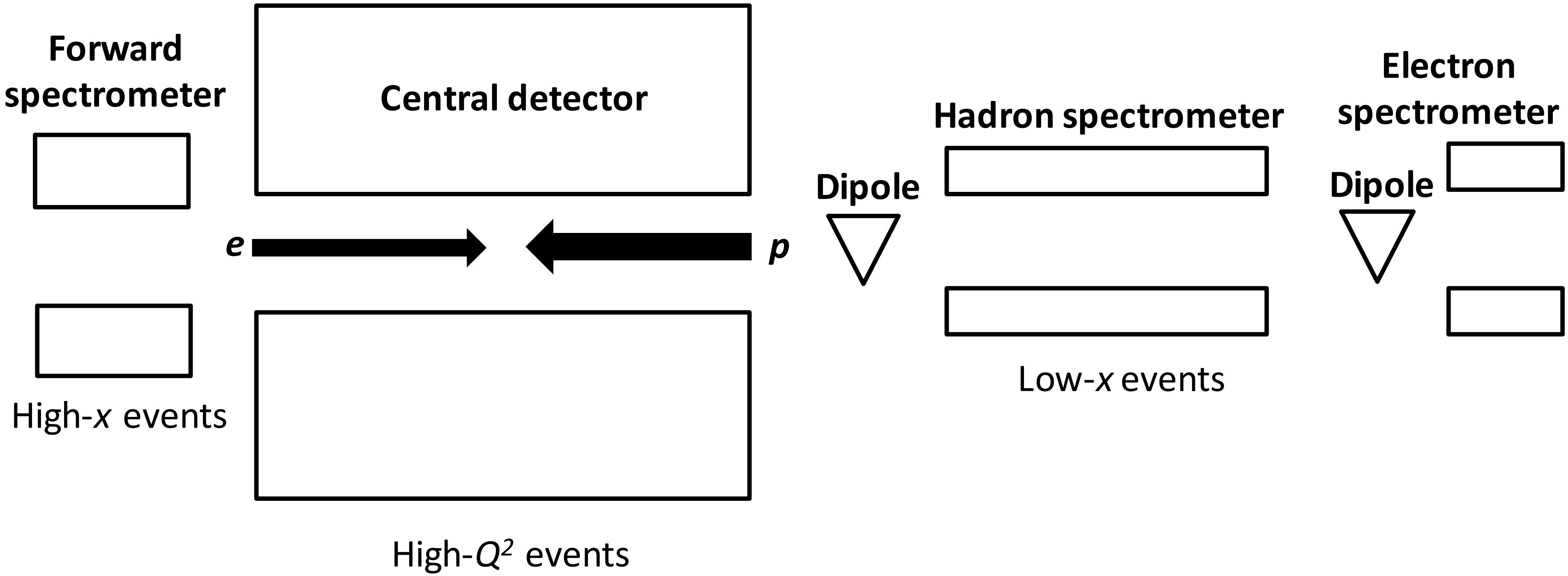
- Access down to $x \sim 10^{-8}$ for $Q^2 \sim 1\ GeV^2$.
- Even lower x for lower Q^2.
- Plenty of data at low x and low Q^2 ($L \sim 0.01\ pb^{-1}$).
- Can go to $Q^2 \sim 10^5\ GeV^2$ for $L \sim 1\ pb^{-1}$.
- Powerful experiment for low-x physics where luminosity less crucial.

Kinematics of the final state



- Generated ARIADNE events with $Q^2 > 1\ GeV^2$ and $x > 10^{-7}$
- Test sample of $L \sim 0.01\ pb^{-1}$
- Nice kinematic peak at *3 TeV*, with electrons scattered at low angles.
- Hadronic activity in central region as well as forward and backward.
- Hadronic activity at low backward angles for low x.
- Clear implications for the kind of detector needed.

Sketch of detector



- Will need conventional central colliding-beam detector.
- Will also need long arm of spectrometer detectors which will need to measure scattered electrons and hadronic final state at low x.